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PHYSICAL FUEL PROPERTIES OF PONDEROSA PINE FOREST FLOORS AND CHEATGRASS

BY JAMES K. BROWN

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PHYSICAL FUEL PROPERTIES OF PONDEROSA PINE FOREST FLOORS AND CHEATGRASS

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JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's from Yale University in 1961, and his Ph.D. from the University of Michigan in 1968; all in Forestry. From 1961 to 1965, he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965 he transferred to the Northern Forest Fire Laboratory, Missoula, Montana, where he is responsible for research on the physical properties of fuel. This paper is based upon a portion of the author's dissertation for his Ph.D. degree, which was entitled "Quantitative Description of Certain Physical Properties of Ponderosa Pine Forest Floor and Cheatgrass Fuels."

The author wishes to express his appreciation to Orval Gastineau, Forest Research Technician at the Northern Forest Fire Laboratory, who performed many of the field and laboratory measurements and computations.

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ABSTRACT

Physical fuel properties were determined utilizing measurements of volume, surface area, and weight for ponderosa pine forest floors and cheatgrass. Average values of these properties for ponderosa pine needle litter and cheatgrass were respectively: surface area-to-volume ratio (σ), 57.6 and 144.0 cm.^{2}/cc.; particle density, 0.51 and 0.34 g./cc.; loading, 324 and 53 g./m.^{2}; void volume-to-surface area ratio (λ), 0.8 and 12.5 cc./cm.^{2}; average particle spacing, 0.66 and 1.70 cm.; bulk density, 0.016 and 0.00032 g./cc.; and $\sigma\lambda$, 37.5 and 1810. Also presented are volume and surface area proportions of the forest floor litter and of the cheatgrass. A goodness-of-fit test showed that pine needles were randomly oriented in the horizontal plane and that cheatgrass particles were nonrandomly oriented in the vertical plane. Correlation analysis indicated that bulk density and particle spacing could be substituted for λ, a fairly difficult variable to measure.

INTRODUCTION

Objective, reliable assessment of potential fire behavior, especially for land managers not intimately familiar with fuels and fire behavior, depends upon the ability to recognize and describe quantitatively certain physical properties of fuel. Development and use of mathematical models for assessment of probable fire behavior on wildfires and prescribed burns particularly require quantification of fuel properties. Quantitative description of fuel properties will be a necessity as the science of fire is developed and more of its principles are applied to solving practical problems.

Like most living things, forest and range fuels are assortments of plant parts and have definite bodily form depending on inherent qualities and environmental conditions. The individual plant is composed of distinctly different parts or organs; for example, flowers, stems, leaves, roots, buds, petioles, bark, and thorns. The wide variety of living and dead plant parts that exist are actually *fuel particles* of varying sizes and shapes. A collection of fuel particles can be termed a *fuel complex.*

This paper reports values for the following physical properties and their relationships to one another for ponderosa pine *(Pinus ponderosa* Laws.) forest floor and cheatgrass (*Bromus tectorum* L.) fuels:

1. Particle size - σ (ratio of particle surface area to volume)
2. Particle density (weight per unit volume)
3. Loading (weight per unit ground area)
4. Porosity:
    a. Ratio of void volume in fuel complex to surface area of fuel - λ
    b. Particle spacing (average distance between fuel particles)
    c. Bulk density (weight per unit volume of fuel complex)
5. $\sigma\lambda$ (a dimensionless fuel complex parameter)
6. Particle orientation (position in space).

Except for particle orientation, the fuel properties were chosen for study because of their significant influence on ignition probability, rate of fire spread, and fire intensity. For example, the ratio σ is a particularly meaningful measure of fuel particle size because of its relationship to rates of change in fuel temperature and in moisture content. Temperature and moisture content of thin fuel particles having a high surface-to-volume ratio generally fluctuate more rapidly than thick particles having a low surface-to-volume ratio (Fons 1950; King and Linton 1963). Controlled combustion studies have shown that ignition time varies inversely with σ (Curry and Fons 1938) and rate of fire spread varies in direct proportion to σ (Rothermel and Anderson 1966).

Particle density is primarily an important fuel property because of its influence on thermal conductivity and consequent influence on time to ignition.[1] Whether or not ignition of a fuel is of the pilot-flame or spontaneous type also depends on particle density.

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[1] D. S. Stockstad. Ignition properties of fine forest fuels. Unpublished problem analysis, Intermountain Forest and Range Exp. Sta., Ogden, Utah. 1967.

Loading is an important property of fuel because it expresses an amount of fuel energy or potential fire intensity. Taken alone, however, it is not an adequate predictor of fire behavior because other fuel properties, such as moisture content, porosity, particle size, and chemical composition, also determine the amount and rate of fuel energy release.

Porosity is the inverse expression of compactness. Porosity relates to the spacing of fuel particles and affects ignition time and combustion through its influence on oxygen supply and radiant energy transfer between particles. Several studies using wooden cribs and pine needle beds have shown that various measures of burning rate increase with increasing porosity up to a certain point (Curry and Fons 1940; Gross 1962; Byram et al. 1964; Anderson et al. 1966). According to Byram, increasing the stick spacing in a fuel complex increases the transmission of radiant heat in the direction of the unburned fuel. But if spacing is too great, unburned particles may not receive enough heat for ignition. If sticks are too closely spaced, sustained burning will not be possible because of restricted airflow. Maximum fire spread occurs between these limits.

Recent research shows that burning characteristics are related to $\sigma\lambda$ (a dimensionless variable) (Rothermel and Anderson 1966). Both particle size and porosity are incorporated in $\sigma\lambda$. Burning characteristics of different fuels possibly may be rated on the basis of $\sigma\lambda$, although more research is needed to demonstrate this conclusively. Past combustion studies involving $\sigma\lambda$ have dealt only with a single particle size. Mixtures of particle sizes certainly need study as well.

The significance of particle orientation in combustion of forest and range fuels is probably minor compared to other fuel properties, although its exact role is not understood. Particle orientation does affect the aerodynamic drag in a fuel complex and probably affects exposure to incident radiation. The forced convection heat transfer coefficient for blue spruce (*Picea pungens* Engelm.) foliage has been shown to vary according to orientation of foliage with respect to direction of airflow (Tibbals et al. 1964).

The fuels studied were collected in western Montana and occur widely throughout the West and are highly flammable. No effort was made to inventory fuel characteristics throughout areas where these two types occur; rather, we sought to obtain an idea of the range in values of fuel properties encountered in these types of fuel and to test techniques of measurement.

SAMPLING PROCEDURES

Ponderosa Pine Forest Floors

Forest floor material was sampled in 13 ponderosa pine stands within 20 miles of Missoula, Montana. The stands ranged from open to closed in density. They were 52 to 99 years of age and occurred on poor, medium, and good sites (figs. 1 and 2). Pine needles and miscellaneous particles, which include staminate flowers, cone scales, cones, bark flakes, branches, grass, and flat leaves, comprised the forest floor (fig. 3).

In each stand, five plots, 1 foot square, were randomly located and photographed in stereo to provide a permanent visual record of the fuel before disturbance. Depth of the litter, or L layer,[2] was measured at four positions (fig. 4) using a rule sliding

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[2] The layers of the forest floor are defined in a glossary of terms approved by the Terminology Committee of the Soil Science Society of America (1965) as: L layer--the surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits; F layer--a layer of partially decomposed material with portions of plant structures still recognizable; and H layer--a layer occurring in mor humus consisting of well-defined organic matter of recognizable origin.

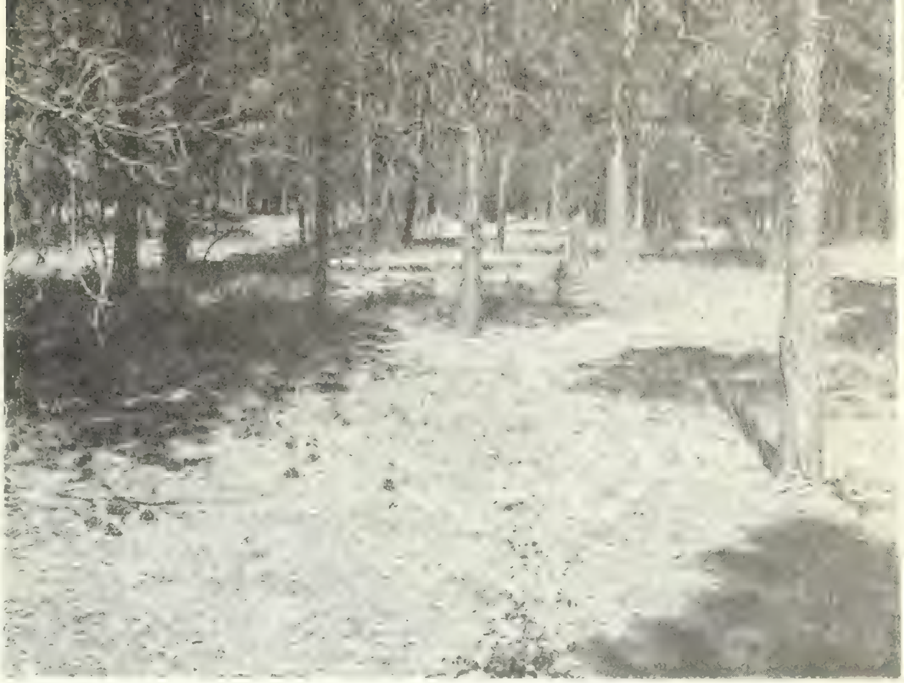

Figure 1.--This 80-year-old open stand of ponderosa pine, which contained 220 trees per acre and 110 square feet of basal area, averaged 231 grams per square meter (2,060 lbs./acre) of fuel in the litter layer.

through a wood frame that measured 1 by 4 inches on the bottom side. The end of the rule was placed at the top of the F layer[3] and the frame was lowered to what appeared as the top of the L layer. Depth was recorded where the frame intersected the rule. Occasional single needles sticking above the general level of the L layer were depressed. Identification of the top of the F layer was fairly easy due to the bound condition (resulting from fungal mycelium) of the F material. Depth of the L layer was used to calculate the volume of the fuel complex for each plot.

A metal frame, 1 foot square, was positioned over the plot and the number of particles crossing under the frame was counted along two adjacent sides for calculation of particle spacing (fig. 4). Particle orientation was ocularly estimated for a minimum of 10 particles per side. The angle made by the intersection of a particle with an imaginary extension of the bottom of the metal frame was judged as one of six adjacent 30°-wide sectors. Orientation was recorded in the horizontal direction because practically all particles lie in this direction due to the influence of gravity. This

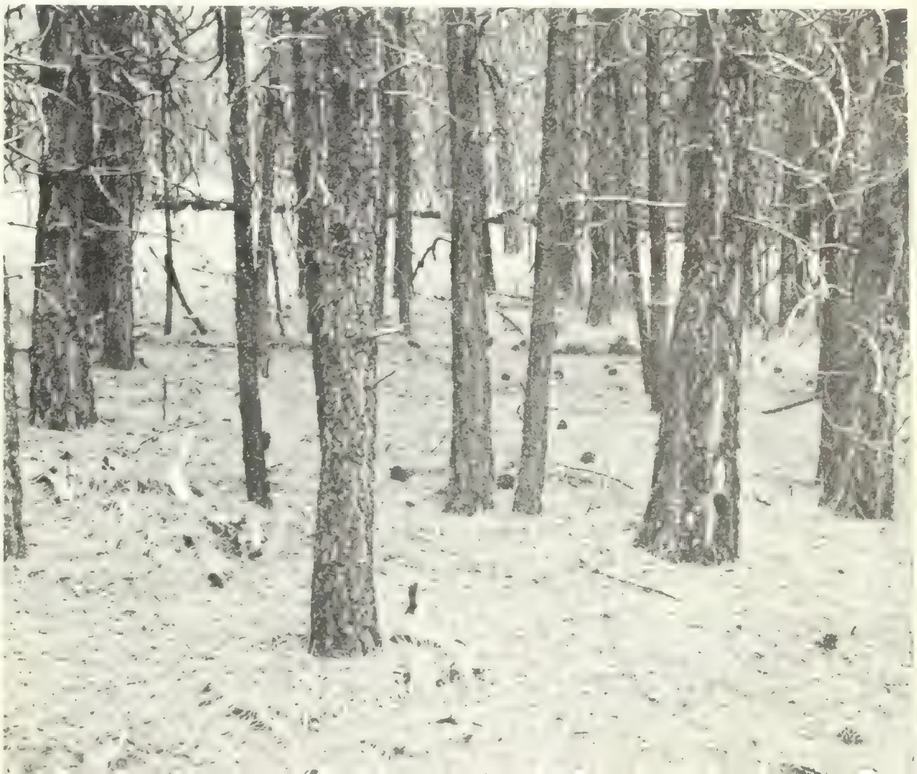

Figure 2.--This 60-year-old dense stand of ponderosa pine, which contained 2,700 trees per acre and 230 square feet of basal area, averaged 415 grams per square meter (3,680 lbs./acre) of fuel in the litter layer.

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[3] Ibid.

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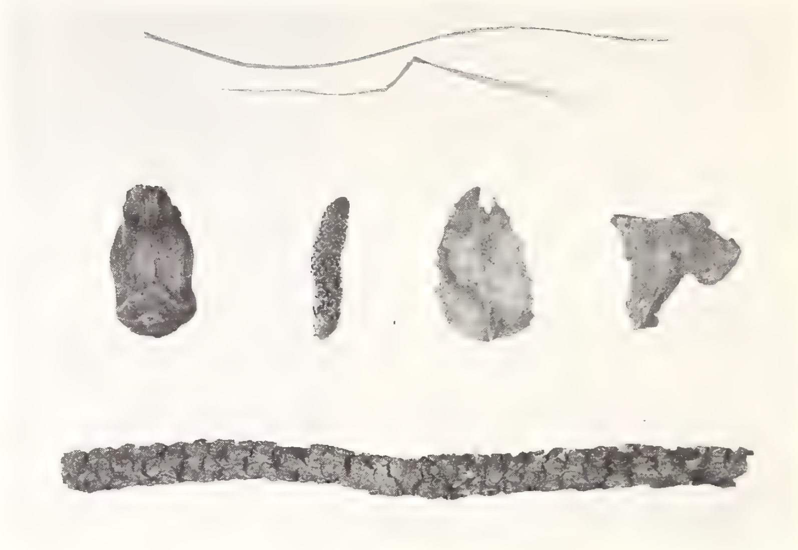
Figure 3.--Grass blades (top); cone scale, staminate flower leaf of woody plant, bark flake (from left to right, middle); and branchwood (bottom) were miscellaneous particles found in the litter.



data was used to estimate randomness of particle orientation and for testing a planar intersect method for estimating fuel volume and surface area.[4]

After the litter was collected, the depth of the F layer was measured where the perpendicular bisectors intersected the edges of the plot. Bulk density was computed on an ovendry weight basis. Very little material collected below the L layer could be identified as H layer material (Soil Sci. Soc. Amer. 1965, p. 9).

Cheatgrass

Cheatgrass plots were established on a slight slope in a south-facing area approximately 1 acre in size 6 miles west of Missoula, Montana (fig. 5). Six kinds of fuel particles--stalks, leaves, peduncles, glumes, spikelets, and awns--were sampled separately (fig. 6).

Three zones containing heavy, moderate, and sparse amounts of fuel were delineated on the ground. Plots 30 by 45 centimeters in size were randomly located in all three zones. All fuel and approximately 5 centimeters of soil were lifted undisturbed into flats and transferred to the laboratory for measurements. The measurements were actually taken from an area 10 by 25 centimeters in each plot. A larger amount of fuel than needed for measurements was collected to avoid disturbing fuel along the small plot edges during the lifting process.

In the laboratory, 15 sampling planes were randomly positioned through the fuel in each plot using a sliding wire frame to delimit the sampling plane (fig. 7). The wire frame, 2.5 centimeters wide, was moved horizontally through the fuel at various elevations for a distance of 10 centimeters. Numbers of particles, by kinds, passing through or touching the sampling plane were recorded; their angle of orientation with respect to the sampling plane was estimated ocularly. For cheatgrass, locating sampling planes horizontally facilitated the counting of particle intersections since particles were oriented dominantly in the vertical direction. Particle orientation was judged only with respect to the vertical direction.

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[4] J. K. Brown. A planar intersect method for sampling fuel volume and surface area. Intermountain Forest and Range Exp. Sta., Ogden, Utah 84401. (In preparation.)

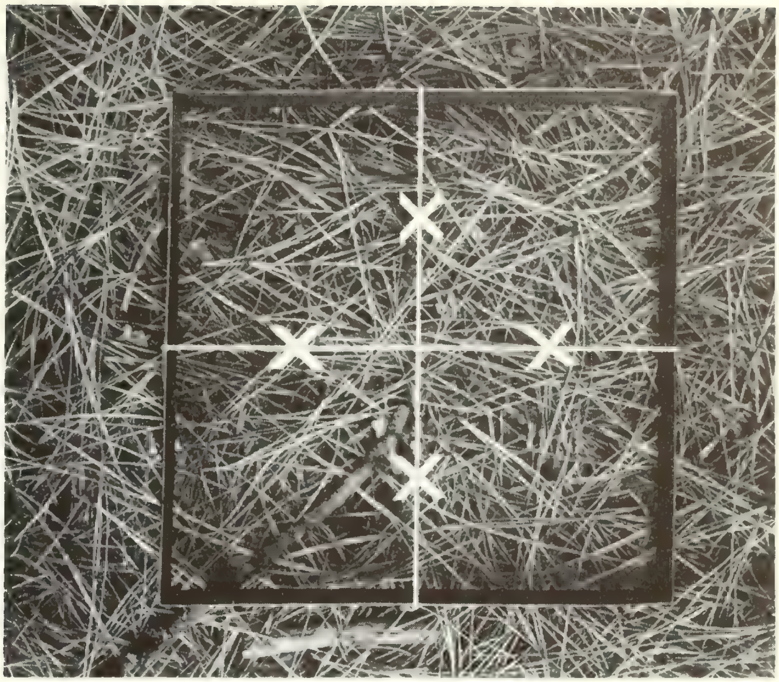

Figure 4.--The metal frame delineates a 1-foot-square plot upon the forest floor of ponderosa pine. Depth of the L layer was measured along perpendicular bisectors of the plots at locations marked "X."

Depth of fuel complex was measured as the distance from the ground to an average height regarded as the general level across the top of the cheatgrass. Occasional cheatgrass parts existing above what appeared as the general top level were excluded from all measurements. All cheatgrass inside the 10- by 25-centimeter plots was carefully clipped, removed, and dissected into the six kinds of particles for determining surface area and volume. The small amount of litter present (mostly fallen spikelets) was excluded from measurements.

VOLUME, SURFACE AREA, AND DENSITY MEASUREMENTS

Volume and surface area of pine needles and cheatgrass were determined from volume-per-gram and surface-per-gram factors multiplied by weight in grams of each type of particle on each plot. These factors were determined from measurements of surface area, volume, and weight for a subsample of particles collected from the study areas.

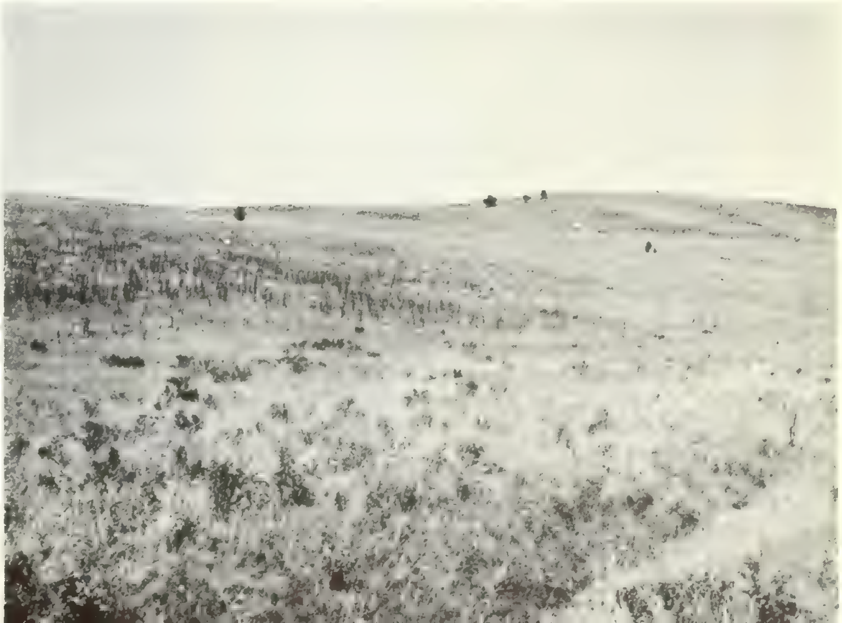

Figure 5.--Cheatgrass, the predominant vegetation in this area, averages 53 grams per square meter (470 lbs./acre). Other plant species visible are balsamroot (Balsamorhiza sagittata *Nutt.*), *moth mullein* (Verbascum blattaria *L.*), *and daisy* (Erigeron *spp.*).

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Figure 6.--Drawing showing parts of a cheatgrass plant.

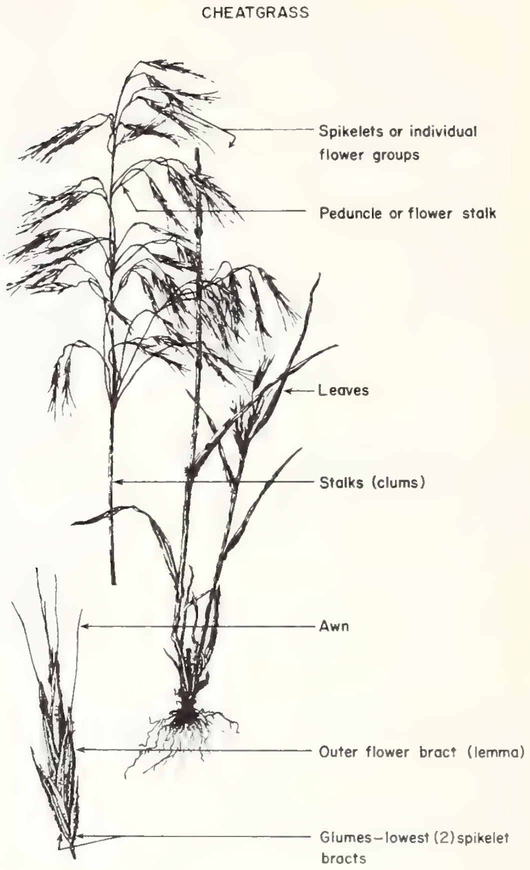
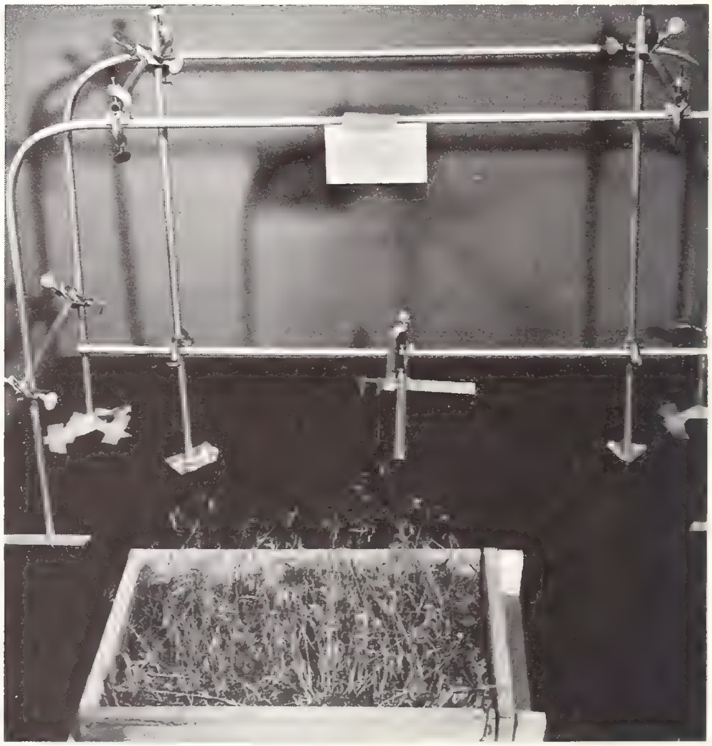

CHEATGRASS
Spikelets or individual flower groups
Peduncle or flower stalk
Leaves
Stalks (clums)
Awn
Outer flower bract (lemma)
Glumes–lowest (2) spikelet bracts

Figure 7.--Apparatus for sampling cheatgrass. The two wires on a movable tract in the center of the picture delineate the sampling plane.



Both surface area and volume were measured on the same fuel specimen to aid in accurately determining surface-to-volume ratios. Sample material was at a moisture content of 5 to 8 percent. For long, narrow particles (pine needles, cheatgrass stalks, peduncles, awns, and spikelets), volume and surface area were determined using measurements of particle cross-sectional area, perimeter, and length. Cross-sectional area and perimeter of pine needles were measured using photomicrographs of right-angled cross sections. Diameters measured microscopically permitted calculation of cross-sectional area and perimeter of the cheatgrass particles.

For flat particles (cheatgrass leaves and glumes and miscellaneous leaves in the forest floor), volume and surface area were determined using measurements of leaf thickness and blueprint outlines of leaf areas.

An electrolytic technique similar to that developed by Tibbals et al. (1964) employing silver castings was used to estimate surface area for cone scales. Volume was determined by displacement in water. Volume and surface area for the staminate flowers, bark flakes, and grass were determined from counts of number of particles in each plot and estimates of their average dimensions. For complete details on measurement of volume and surface area see Brown (1970).

Particle density was determined using ovendry weights and airdry (5- to 8-percent moisture content) volumes.

CALCULATIONS OF $\sigma\lambda$, PARTICLE SPACING, AND ORIENTATION

Most of the properties are calculated from measurements in a manner obvious from their definitions. Calculations of $\sigma\lambda$, particle spacing, and orientation, however, are not so obvious. It is necessary to determine an average σ in calculating $\sigma\lambda$ for fuel complexes, where more than one particle size is present. In this study, where six to eight different particles existed, σ was calculated as an average, weighted by volume of each type of particle present.

Spacing of particles, as viewed in the sampling plane, is computed from

$$Sp = \sqrt{Vd} - \sqrt{A} \qquad (1)$$

where:

Sp = average particle spacing,

Vd = void space per particle, and

A = average cross-sectional area of particles.

It is assumed that particles are square in cross section and that void space is distributed evenly about each particle. Solution of equation (1) requires knowledge of average right cross-sectional area of particles and sample information on the number of particle intersections with a sampling plane. Void space per particle equals the area of sampling plane divided by number of particle intersections.

The following two hypotheses were subjected to the chi-square test for goodness-of-fit for evaluating randomness of particle orientation: (1) Ponderosa pine needles are randomly oriented in a horizontal plane; (2) cheatgrass particles are randomly oriented in a vertical plane.

The number of particle intersections in each of the six 30°-wide sectors arcing about one side of the sampling plane was compared with the expected number of particle intersections in these sectors.

The expected number of particle intersections (E) was calculated from

$$E_{(0^\circ - 30^\circ)} = 0' \int_{0^\circ}^{30^\circ} \sin \theta d\theta$$

$$E_{(30^\circ - 60^\circ)} = 0' \int_{30^\circ}^{60^\circ} \sin \theta d\theta$$

$$E_{(60^\circ - 90^\circ)} = 0' \int_{60^\circ}^{90^\circ} \sin \theta d\theta$$

where 0' equals total number of observed particle intersections in all six 30°-wide sectors.

These calculations are appropriate because the probability of a randomly positioned plane intersecting a particle is proportional to the sine of the angle between particle and plane (Kendall and Moran 1963). Consequently, the number of particles intersected at any angle is also proportional to the sine of the angle of intersection.

RESULTS AND DISCUSSION

Surface-to-Volume Ratios

Two observations of σ on each of 13 ponderosa pine needles of average thickness averaged 57.57 square centimeters per cubic centimeter with a standard deviation of 6.81 square centimeters per cubic centimeter.

Average σ for the entire cheatgrass plant was 144.03 square centimeters per cubic centimeter. This average, as well as average density, was weighted according to volume of each particle found on all plots. Table 1 summarizes average values of σ for the six cheatgrass particles.

Table 1.--Averages and measures of variation of surface area-to-volume ratios for six particles comprising cheatgrass

Kind	Average surface-to-volume ratio	Number of observations	Standard deviation	Coefficient of variation
	$Cm.^2/cc.$		$Cm.^2/cc.$	Percent
Stalks	75.8	880	5.8	7.6
Leaves	167.4	50	17.7	10.6
Peduncles	277.3	100	14.1	5.1
Spikelets	321.5	5	([1])	([1])
Awns	331.7	20	75.4	22.7
Glumes	709.1	9	130.3	18.4

[1] Not calculated.

Table 2.--Average density and its variation for six particles comprising cheatgrass

Kind	Average density	Number of observations	Standard deviation	Coefficient of variation
	G./cc.		G./cc.	Percent
Stalks	0.36	10	0.03	8.4
Leaves	.25	10	.02	7.9
Peduncles	.51	10	.06	12.0
Spikelets	.57	5	([1])	([1])
Awns	.59	15	.28	46.6
Glumes	.21	15	.03	12.7

[1] Not calculated.

Density

Density of ponderosa pine needles free of decay averaged 0.51 gram per cubic centimeter with a standard deviation of 0.046 gram per cubic centimeter for thirteen 10-needle samples. Decay of needles ordinarily reduces their density as was evidenced in another sample of needles, some slightly gray in color and harboring incipient decay. Density of this sample, determined for 620 needles from three stands, averaged 0.47 gram per cubic centimeter.

Density for the entire cheatgrass plant averaged 0.34 gram per cubic centimeter (table 2). Density of stalks is based on a volume figure containing some void space, since the centers of the larger stalks are hollow. Consequently, density of stalk material itself should be greater than density of the entire stalks. Density of awns varied considerably, most likely because their shapes were assumed to be frustrums of right cones; whereas in truth, they vary from elliptical to circular in cross section. Their irregular shape and minute size made accurate determination of their volume difficult.

Table 3.--Fuel properties of the forest floor L layer from 13 stands of ponderosa pine

Fuel property	Highest stand [1]	Lowest stand	Average	S.E. [2]
Loading (g./m.^{2}) [3]	601	129	324	62
λ (cc./cm.)	1.23	.45	.82	.08
Particle spacing (cm.)	.90	.44	.66	.04
Bulk density (g./cc.) [3]	.0429	.0049	.0158	.0033
$\sigma\lambda$	58.5	20.0	37.5	4.9

[1] Stand values are averages from five plots.

[2] Standard error of stand averages equals $\sqrt{\frac{\text{mean square for error}}{\text{treatment replications}}}$ where values for this calculation are provided from an analysis of variance with stands as treatments (Steel and Torrie 1960, page 104).

[3] Ovendry basis.

Loading of Fuel Complex

Loading for the ponderosa pine forest floor litter averaged 324 grams per square meter (2,890 lbs./acre) and ranged between 129 and 601 grams per square meter (table 3). These values compare with 630 grams per square meter for litter in natural red pine (*Pinus resinosa* Ait.) stands and 380 grams per square meter for litter from jack pine (*Pinus banksiana* Lamb.) plantations in the Lake States (Brown 1966). In Alabama, litter in second-growth longleaf pine (*Pinus palustris* Mill.) stands ranged from 290 to 477 grams per square meter (Boyer and Fahnestock 1966).

The litter layers ranged from 1 to 3 centimeters in depth. The entire forest floor (decomposed and undecomposed material together) averaged 5 centimeters in depth and 2,623 grams per square meter (23,400 lbs./acre).

Loading for cheatgrass averaged 53 grams per square meter (470 lbs./acre), as shown in table 4. This average is not necessarily typical of cheatgrass production in western Montana but is probably low, since little rain fell during the spring growing season, which resulted in small yields. At Arrowrock, Idaho, cheatgrass yielded 42 grams per square meter (airdry) one year and 388 grams per square meter the next year (Hull and Pechanec 1947). This tenfold increase shows how production of cheatgrass can vary from year to year.

Table 4.--Averages for fuel properties from a 1-acre cheatgrass community

Item	Dense zone[1]	Moderate zone	Sparse zone	All plots[2]
Number of plots	11	20	7	38
Loading (g./m.^{2})[3]	77.1 [4](4.7)	53.2 (6.1)	15.7 (.7)	53.1
λ (cc./cm.^{2})	6.98 (2.06)	10.97 (4.72)	25.47 (8.46)	12.49
Particle spacing (cm.)	1.22 (.15)	1.76 (.58)	2.29 (.30)	1.70
Bulk density (g./cm.^{3})[3]	$4.42X10^{-4}$ $(.66X10^{-4})$	$3.16X10^{-4}$ $(1.10X10^{-4})$	$1.24X10^{-4}$ $(.45X10^{-4})$	$3.17X10^{-4}$
$\sigma\lambda$	1010 (30)	1590 (60)	3690 (100)	1810

[1] The zones were delineated on the ground according to visual inspection of density of the cheatgrass.

[2] Mean weighted by number of plots.

[3] Ovendry basis.

[4] The numbers in parentheses are standard deviations.

Porosity of Fuel Complex

Void Volume-to-Surface Area

Porosity values determined in this study may be of particular interest for relating laboratory research on fire propagation to field conditions. One expression of porosity, λ, is the amount of void space associated with a unit area of fuel surface. Generally, movement of air and gases is freer as λ increases because the space between particles is greater. However, the distance that radiant heat must travel between particles is also greater.

Cheatgrass, averaging 12.5 cubic centimeters of void per square centimeter of surface, was 15 times more porous than the ponderosa pine forest floor litter which averaged 0.8 cubic centimeter per square centimeter. The greater porosity of cheatgrass is no doubt more conducive to rapid fire spread than the lower porosity of ponderosa pine litter.

Particle Spacing

Particle spacing is also a measure of the porosity of a fuel complex. Spacing between cheatgrass particles was 2-1/2 times greater than was spacing between particles in the ponderosa pine forest floors. Particle spacing, λ, and bulk density, even though they all indicate porosity, do not correlate perfectly because they are measured differently. Among the three, particle spacing showed the least difference between the forest floor litter and cheatgrass.

Bulk Density

Bulk density is an approximate measure of porosity of a fuel complex. It fails to precisely express the amount of fuel complex occupied by actual fuel volume because the specific gravity of fuel is disregarded. Thus, only weight, and not volume of fuel, is corporated in an expression of bulk density. Nonetheless, it does indicate a degree of porosity and has the practical advantage of being easy to measure.

The bulk density of cheatgrass averaged 0.00032 gram per cubic centimeter, which was 50 times less dense than the average of 0.016 gram per cubic centimeter for the litter. The F layer from the forest floors averaged 0.076 gram per cubic centimeter and ranged from 0.039 to 0.105 gram per cubic centimeter. This is approximately one-half as dense as bulk densities reported for humus of western white pine (*Pinus monticola* Dougl.), hemlock (*Tsuga heterophylla* (Rafn.) Sarg.), and Douglas-fir (*Pseudotsuga menziesii* (Poir.) Britt.) forests (Mader 1953) but practically the same as reported for red pine forests (Brown 1966). Depth of the F layer averaged 3 centimeters.

Proportions of Particles

Pine needles, averaged over all stands, comprised a little over one-half of the volume in the forest floor litter and approximately 90 percent of the fuel surface area. Miscellaneous particles accounted for the remainder. The proportions of needles and miscellaneous particles in the litter varied substantially from stand to stand. Needles comprised 43 to 79 percent of the volume and 78 to 97 percent of the surface area of the forest floor litter.

Among the miscellaneous particles, branches contributed by far the most volume but only slightly more surface area than cone scales as shown in the following tabulation:

Particle	Volume (Percent)	Surface area (Percent)
Branches	51.2	26.4
Cones	21.4	4.3
Cone scales	11.4	25.1
Bark	8.0	13.2
Staminate flowers	4.9	4.4
Leaves	2.4	19.6
Grass	.7	7.0
	100.0	100.0

In cheatgrass, stalks comprised almost two-thirds of the volume but only one-third of the surface area. The panicles (spikelets, glumes, and peduncles) comprised only a small portion of the total volume but a little over one-third of the surface area as shown in the following tabulation:

Plant part	Volume (Percent)		Surface area (Percent)	
Stalks	61		32	
Leaves	25		29	
Panicles:	14		39	
Spikelets		9		19
Glumes		3		15
Peduncles		2		5
	100		100	

Randomness of Particle Orientation

Forest and range fuels are composed of particles oriented in many directions. However, apparently no studies have been conducted that analytically define the randomness of particle orientation or the type of predominant orientation. Particle orientation should be taken into account when designing and using sampling methods for measuring fuel properties in the field.

Pine needles were randomly oriented (at the 0.01 confidence level) in the horizontal plane for all stands combined as well as for 12 of the 13 stands individually. In the one stand, the tip of a branch fell across the sampling plane on one plot so that a large number of needles attached to the branch lay in one direction. Such situations can be expected to occur sporadically in the forest. All stands grew on flat to moderately sloping terrain. Whether or not the generally random orientation of needles would hold on steep slopes is conjecture.

All six kinds of cheatgrass particles were nonrandomly oriented in the vertical plane. Except for glumes, the other particles were oriented predominantly within 30° of true vertical. A considerably greater number of glumes than expected under a random assumption were oriented within 30° of true horizontal.

Relationships Between Properties

Relationships between fuel properties were examined to see whether or not some fuel properties may be replaced by or estimated from other fuel properties or from sample data on number of particle intersections. The relationships between the three properties describing porosity are shown by the correlations in figure 8.

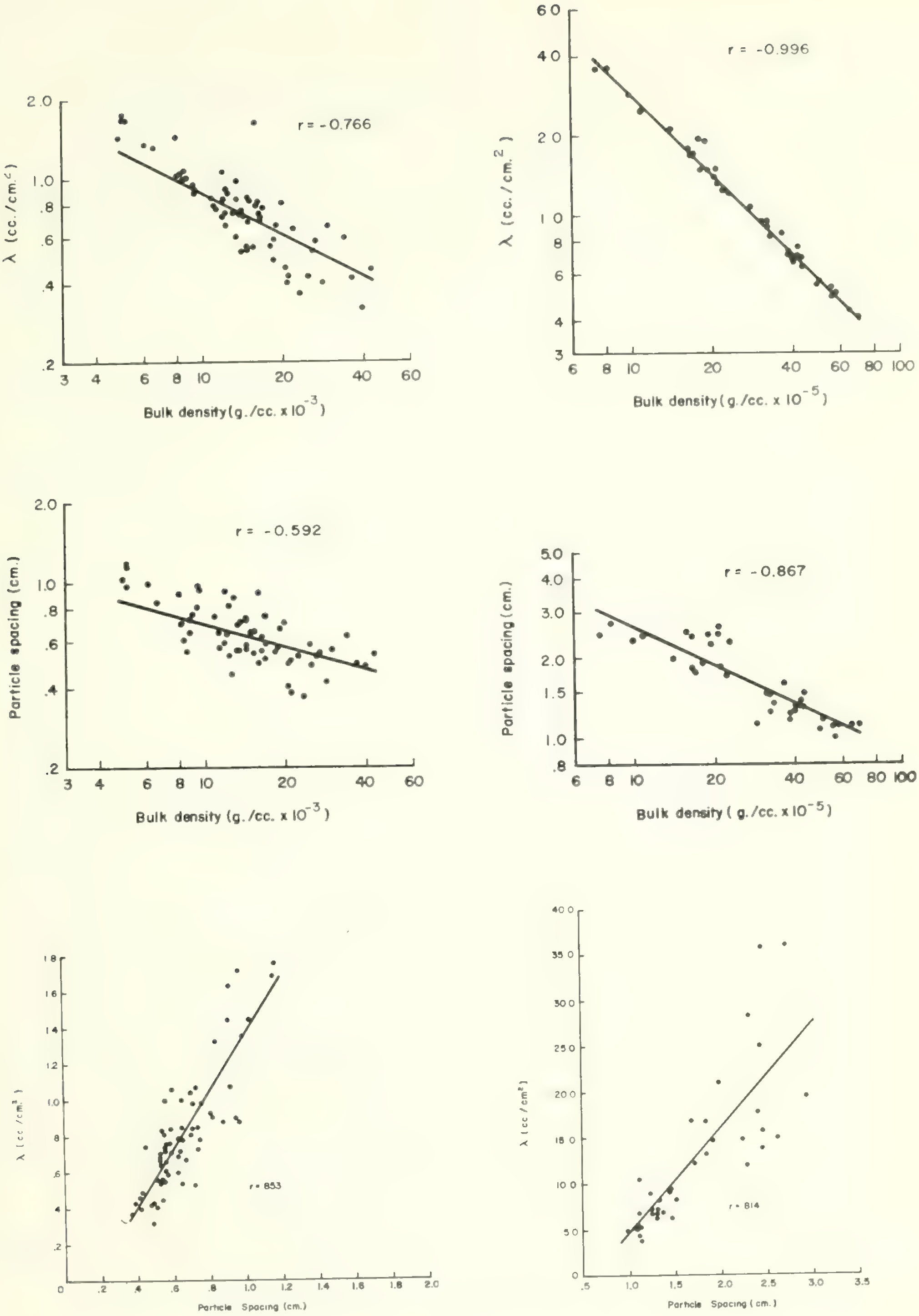


Figure 8.--Correlations between measures of the porosity of a fuel complex for ponderosa pine forest floor litter (left) and cheatgrass (right). The r values are significant at the 0.01 probability level and lines fitted by method of least squares.

The practical implication from these correlations is that particle spacing and bulk density possibly may be used as a substitute for λ or to estimate λ in other fuels as well as those studied. Measurement of λ entails considerable work because knowledge of fuel surface area and volume is required for its computation. In many fuels, it would be easier to determine spacing by actually sampling the distances between particles or by counting the number of particle intersections with a sampling plane. Bulk density can be determined readily by measuring fuel weight and dimensions of the fuel complex from a sample of plots. It is uncertain which of the three properties--bulk density, particle spacing, or λ--provides the most accurate description of porosity. Perhaps more accurate expressions of porosity than these three can be developed.

REFERENCES

Anderson, Hal E., A. P. Brackebusch, R. W. Mutch, and R. C. Rothermel.
1966. Mechanisms of fire spread, research progress report no. 2. U.S. Forest Serv. Res. Pap. INT-28, 24 p., illus.

Boyer, W. D., and G. R. Fahnestock.
1966. Litter in longleaf pine stands thinned to prescribed densities. U.S. Forest Serv. Res. Note SO-31, 4 p., illus.

Brown, James K.
1966. Forest floor fuels in red and jack pine stands. U.S. Forest Serv. Res. Note NC-9, 3 p., illus.

______ 1970. Ratios of surface area to volume for common fine fuels. Forest Sci. 16(1): 101-105, illus.

Byram, G. M., H. D. Clements, E. R. Elliott, and P. M. George.
1964. Technical report no. 3--an experimental study of model fires. U.S. Forest Serv., Southeastern Forest Exp. Sta., 36 p., illus.

Curry, J. R., and W. L. Fons.
1938. Rate of spread of surface fires in the ponderosa pine type of California. J. Agr. Res. 57(4): 239-267.

______ and W. L. Fons.
1940. Forest-fire behavior studies. Mech. Eng. 62: 219-225, illus.

Fons, W. L.
1950. Heating and ignition of small wood cylinders. Ind. and Eng. Chem. 42: 2130-2133, illus.

Gross, D.
1962. Experiments on the burning of cross piles of wood. J. Res. Nat. Bur. Stand., C. Eng. and Instrum., 66 C., pp. 99-105, illus.

Hull, A. C., and J. F. Pechanec.
1947. Cheatgrass--a challenge to range research. J. Forestry 45: 555-564, illus.

Kendall, M. G., and P. A. P. Moran.
1963. Geometric probability. New York, Hofner Publishing Co., 125 p.

King, A. R., and M. Linton.
1963. Moisture variation in forest fuels: the rate of response to climate changes. Aust. J. Appl. Sci. 14(1): 38-49, illus.

Mader, D. L.
1953. Physical and chemical characteristics of the major types of forest humus found in the United States and Canada. Soil Sci. Soc. Amer. Proc. 17: 155-158.

Rothermel, R. C., and H. E. Anderson.
1966. Fire spread characteristics determined in the laboratory. U.S. Forest Serv. Res. Pap. INT-30, 34 p., illus.

Soil Sci. Soc. Amer.
1965. Glossary of soil science terms. Soil Sci. Soc. Amer. Proc. 29(3): 330-351.

Steel, R. G. D., and J. H. Torrie.
1960. Principles and procedures of statistics with special reference to the biological sciences. 481 p., illus. New York, McGraw-Hill Book Co., Inc.

Tibbals, E. C., E. K. Carr, D. M. Gates, and F. Krieth.
1964. Radiation and convection in conifers. Amer. J. Bot. 51: 529-538, illus.

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